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RISING ARCTIC OCEAN TEMPERATURES CAUSE GAS HYDRATE DESTABILIZATION AND OCEAN ACIDIFICATION

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ABSTRACT

Formed under low temperature – high pressure conditions vast amounts of methane hydrates are considered to be locked up in sediments of continental margins including the Arctic shelf regions[1-3]. Because the Arctic has warmed considerably during the recent decades and because climate models predict accelerated warming if global greenhouse gas emissions continue to rise [3], it is debated whether shallow Arctic hydrate deposits could be destabilized in the near future[4, 5]. Methane (CH4), a greenhouse gas with a global warming potential about 25 times higher than CO2, could be released from the melting hydrates and enter the water column and atmosphere with uncertain consequences for the environment. In a recent study, we explored Arctic bottom water temperatures and their future evolution projected by a climate model [1]. Predicted bottom water warming is spatially inhomogeneous, with strongest impact on shallow regions affected by Atlantic inflow. Within the next 100 years, the warming affects 25% of shallow and mid-depth regions (water depth < 600 m) containing methane hydrates. We have quantified methane release from melting hydrates using transient models resolving the change in stability zone thickness. Due to slow heat diffusion rates, the change in stability zone thickness over the next 100 years is small and methane release limited. Even if these methane emissions were to reach the atmosphere, their climatic impact would be negligible as a climate model run confirms. However, the released methane, if dissolved into the water column, may contribute to ocean acidification and oxygen depletion in the water column.

Keywords: gas hydrates, global warming, Arctic, ocean acidification

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INTRODUCTION

Stabilized by year-round cold temperatures, submarine Arctic methane hydrates are deposited at shallow water depth close to shelf edges [6], which make them vulnerable to global warming. In fact, recent field studies indicate an increase in methane fluxes from submarine Arctic permafrost and the seafloor [7, 8]. Here we present the results of a recent comprehensive study of the future fate of Arctic methane hydrates [1]. Our multi-disciplinary analysis provides a closer look into regional developments of submarine Arctic gas hydrate deposits under future global warming scenarios and reveals where and over which time scales gas hydrates could be destabilized and affect oceanic pH, oxygen, and atmospheric methane.

PROJECTED WARMING OF ARCTIC BOTTOM WATERS

For an evaluation of the general distribution and the natural variability we investigated the spatio-temporal variability of Arctic bottom water in a hindcast experiment with the ocean/sea-ice NEMO (v2.3) [1, 9], carried out by the DRAKKAR collaboration [10]. The global simulation was performed at 1/2° resolution (ORCA05) and 46 levels in the vertical, whereby partial bottom cells allowed realistic topographic slopes. The experiment, that demonstrated its fidelity in simulating the salient features of the Atlantic circulation variability [11], was forced by inter-annually varying atmospheric boundary conditions of the past decades [12]. To exclude a potential model drift in the water masses a second experiment under repeated-year forcing was subtracted from the hindcast. The bottom water temperatures to first order reflect water depth, featuring colder values around 0 °C below 1000 m and warmer values on the shelves. However, a clear impact of the ocean circulation is seen as a band of temperatures around 1 °C surrounding the AO at ~400 m, an expression of the Atlantic inflow below the Arctic halocline [13]. Colder temperatures appear on the Russian and Canadian shelves due to the exposure of the surface waters to continental cold air outbreaks during winter.

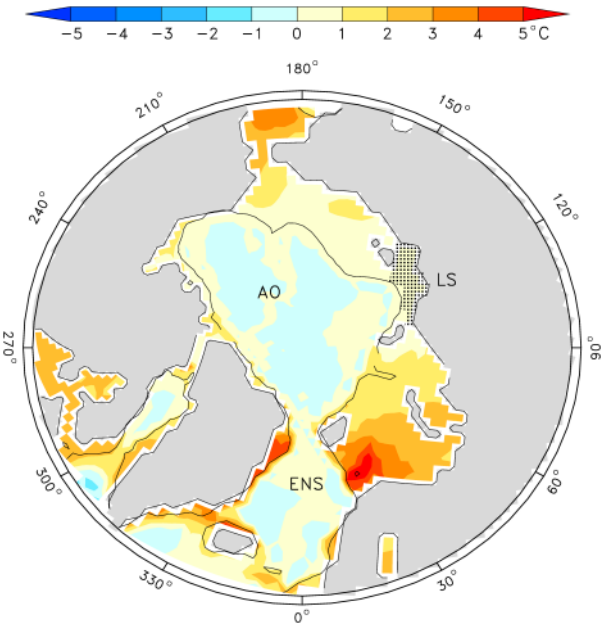

Figure 1: Projected change in Arctic bottom water temperatures over the next 100 years [1].

The future evolution of bottom water temperatures was analyzed in an ensemble of greenhouse warming integrations with a coupled climate model (KCM) [14]. This configuration utilizes the same numerical framework, but at lower resolution (ORCA2, 2° horizontally, 31 levels) and the atmospheric model ECHAM5 [15] as an active atmosphere. In addition to a 430 year control experiment with present day greenhouse gas concentrations (CO_2 = 348 ppm), an ensemble of eight 100-year long global warming simulations, each starting from different states of the control run, were performed with 1% increase in the CO_2 equivalent concentration [14]. The linear trend of the ensemble average was combined with the ORCA05 distribution. The temperature changes (Fig. 1) show a highly inhomogeneous distribution, with increases of 1-2 °C along the continental slopes and even higher values on the shelves due to the direct influence from the atmosphere. Individual ensemble members resembles strong inter-annual to decadal variability in the Nordic Seas due to different states of the Atlantic Ocean circulation, but all feature a consistent long-term trend of 2.5 °C per century. Anomalies take some decades to protrude into the Laptev Sea, depending on the state of the Arctic circulation [13]; consistent trends are starting typically after 50 years.

GAS HYDRATE STABILITY UNDER PRESENT AND GLOBAL WARMING CONDITIONS

Methane hydrate stability in marine sediments is mainly a function of temperature and pressure [16]. For the overall impact of future bottom water warming on the stability of methane hydrates potentially stored in the Arctic seafloor we explored the thickness of the gas hydrate stability zone (GHSZ) below the seafloor. The GHSZ is defined as that part of a sediment column where hydrostatic fluid pressures are higher than the temperature and salinity dependent dissociation pressure of gas hydrates. Arctic sub-seafloor pressures are assumed to be hydrostatic and can therefore be directly calculated from water depth. Bottom water salinities are assumed to be representative for the entire sediment column. Steady-state geotherms for present and future climates are constructed using global heat flow data, computed bottom water temperatures, and a constant thermal conductivity of 1.5 W m-1 K-1.

Impact on Structure I hydrates

The dissociation pressure for pure methane structure I hydrates are calculated according to [16]. Figure 2 shows the projected change in stability zone thickness between the two steady-states. Under Arctic bottom water temperature conditions, structure I methane hydrates are not stable at water depths shallower than 400m and therefore also not below the warming shallow shelf waters (Figure 1). For this reason, Figure 2 shows the clearest reduction in structure I hydrate stability close the 400m water depth contour. Regions that are particular vulnerable to Global Warming induced hydrate melting can clearly be identified. In the European Nordic Seas, the prevalent structure I methane hydrate will experience a clear phase shift from hydrate to free gas in predominantly mid-depth levels at around 400-500 m within the next 100 years.

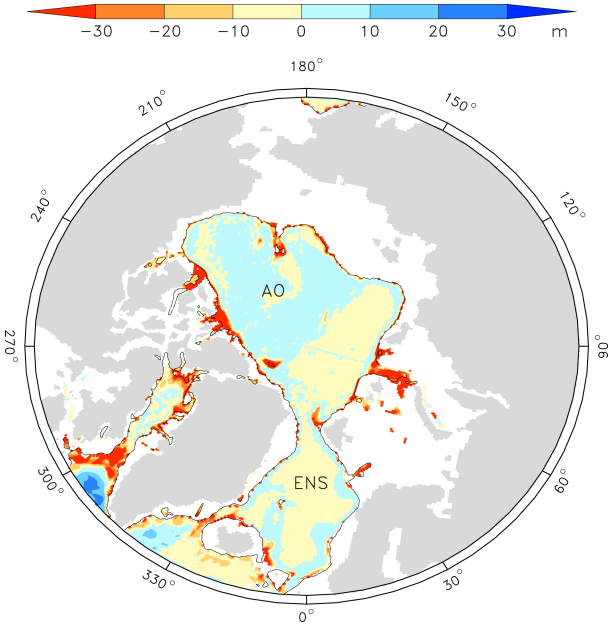

Figure 2: Change in stability zone thickness for structure I hydrates [1].

Impact on structure II hydrates

Figure 1 shows that the most significant warming will occur at shallow water depth < 400m, where structure I hydrates are not stable. However, depending on the presence of other guest molecules, e.g. higher hydrocarbons, during formation, methane hydrates feature different crystal structures (type I, II, and H) with characteristic physical behavior [6]. We have also explored potential shifts in the stability zone of structure II hydrates using an example composition of 96% CH_4, 3% C_2H_6, 1% C_3H_8 and thermodynamic data from the computer program CSMHYD [17]. It is clear from Figure 3 that structure II hydrates would be massively affected in shelf regions – especially those under the Atlantic influence. The abundance of this hydrate type is, however, restricted to hydrocarbon-rich sediments and significant amounts of methane could be released close to shallow oil fields such as located in the Beaufort Sea and Barents Sea [18]. Since it is virtually impossible at the moment to constrain the likely volumes of structure II hydrates present on the Arctic shelves, we will restrict ourselves in the following considerations to structure I hydrates.

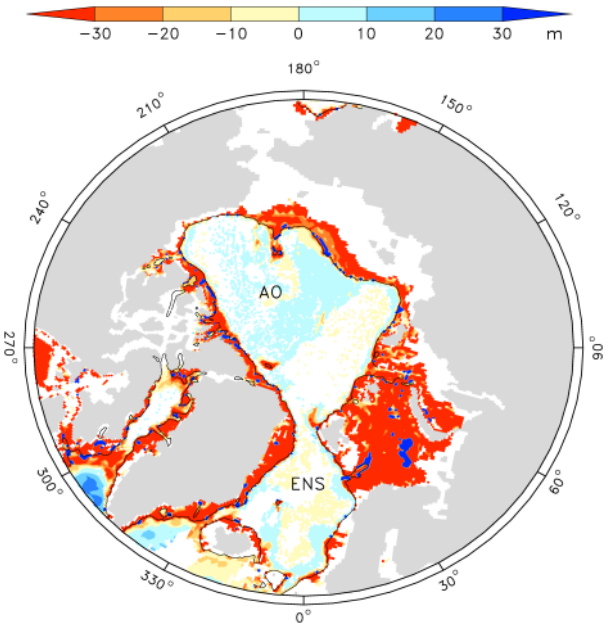

Figure 3: Change in stability zone thickness for structure II hydrates.

Possible consequences of hydrate melting over the next 100 years

In order to assess the importance and potential consequences of this reduction in structure I hydrate stability zone thickness, we need to estimate the amount of hydrates locked up in Arctic sediments. A rough estimate can be done by using simple published constant mean hydrate pore filling estimates of 2.4% (60-70°N) to 6.1% (north of 70°N) based on ODP data and numerical modeling [3]. Inhibition of hydrate formation by sulfate reduction is approximated by including a 5m thick hydrate free zone below the seafloor. Assuming a mean porosity of 0.5 and standard values for density and methane content of hydrate, we estimated a total inventory of 900 Gt carbon north of 60° N for the present climate. This value is not too far off the estimated 500 Gt C based on studies offshore Alaska [19] representing a fraction of the still largely unknown global hydrate inventory of 500-64,000 Gt C [6]. Under the global warming scenario most affected regions are distributed around the AO and the ENS. Areas exhibiting decreases ≥ 20 m in the GHSZ thickness sum up to a total size of ~850,000 km2 resulting in a total methane release of ~100 Gt C.

However, these estimates are too high for the considered 100-year time window and need to be adjusted for the sluggish diffusion of heat into marine sediments. Using a constant thermal diffusivity of 4×10^{-7} m s^{-2} and neglecting the latent heat of hydrate melting, we find that only 12% of the worst-case hydrate volume is reduced after 100 years for sulfate reduction zone thicknesses 5 m.

What could happen to the released methane? It is conceivable from environmental hydrate studies that, depending on the release rate, at least ~50% of the methane that dissolves into the sediment porewater, could be retained inside the seafloor by microbial anaerobic oxidation of methane (AOM) [20, 21]. AOM represents a long-term sink for methane-derived carbon, converting methane into bicarbonate and eventually precipitating a percentage as authigenic carbonates [22]., However, methane rising through sediments as free gas could bypass the benthic methane filter [20] and, depending on water depth [23], immediately reach the atmosphere. Methane that on the other hand dissolves into the water column could be utilized by microbial aerobic oxidation of methane [24], which directly forms CO2 – a molecule that can impact oceanic pH.

For the following scenario we assume that 50% of the methane from the transient GHSZ thickness change is released into the water column and consumed by aerobic methanotrophs. A Lagrangian analysis of the oceanic currents shows that (within a given year) the bulk of the water affected by methane is kept within 100 m above the bottom and along the mid-depth topographic slope. Changes in seawater carbonate chemistry were calculated by adding the microbial produced CO2 to the background dissolved inorganic carbon. Some areas of the AO revealed pH values to drop by up to 0.25 units (Figure 4) within the next 100 years. Additionally, the aerobic consumption of methane could locally decrease bottom water oxygen concentrations by up to 25%. Regional methane-induced seawater acidification from the seafloor would occur in addition to an ocean-wide acidification caused by the uptake of anthropogenic CO2 from the atmosphere [25]. The combined effect of the two processes would accelerate ocean acidification in parts of the AO, including deeper waters which otherwise would be exposed to ocean acidification with a considerable time delay. Research on that topic so far has been conducted under the premises of a projected pH decrease due to the anthropogenic CO2-uptake of about 0.3 units until the end of this century.

Methane-induced acidification could nearly double this decrease in parts of the AO. It should be mentioned that for this scenario we did not consider that also anaerobic consumption of methane could indirectly contribute to ocean acidification, if produced hydrogen sulfide is oxidized back to sulfate with oxygen or nitrate at the sediment-water interface. In this re-oxidation process, protons are released that could further react with bicarbonate to make CO_2 [26]. More in-depth studies are needed to evaluate the importance of this reaction.

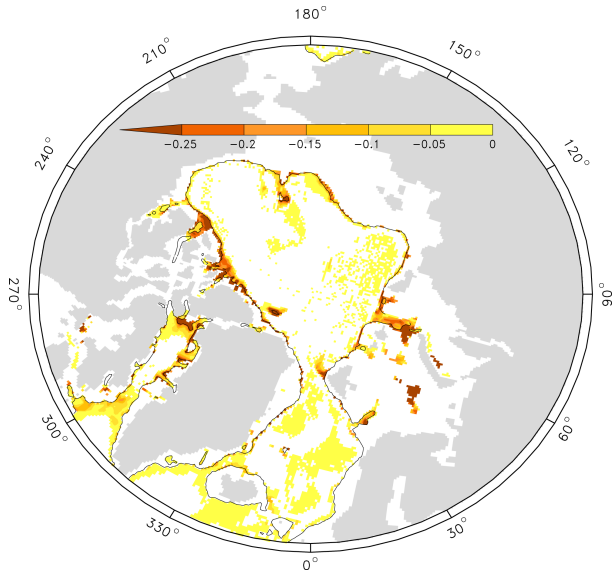

Figure 4: Projected change in ph-level over the next 100 years [1].

If, in a rather unrealistic scenario, all of the liberated methane would reach the atmosphere, global warming could be amplified [27]. Under transient conditions we estimated an additional average methane flux of only 162 Mt CH4 yr-1 from melting Arctic hydrates over the next 100 years – a value lower than the current anthropogenic input of (600 Mt yr-1) [27]. Sensitivity experiments with the climate model confirm the negligible feedback of the climate system under this limited additional amount of methane. On a longer time scale, however, the transient heat conduction leads to a faster methane release; the methane released from the steady-state GHSZ calculation causes an upper limit of 0.7 °C increase in surface air temperature on top of global warming.

CONCLUSIONS

The present study is to our knowledge the first combining ocean hindcasts and future climate projections with GHSZ calculations and potential consequences. It should be noted that the overall model still has its limitation with respect to the resolution of the bottom water temperatures, the actual distribution of sub-seafloor methane hydrates and the individual response of the microbial community in the sediment and water column. Nevertheless, the study clearly shows that hydrate destabilization can occur in the Arctic in response to global warming, and that the potential methane release is substantial, but limited in the next 100 years. An important finding is that warming and variability of the Atlantic inflow will play a major role in the fate of Arctic gas hydrates. Recent observations [7, 28] agree well with sensitive areas identified here. Our maps could represent a useful tool in identifying areas around the Arctic Ocean where increases in methane release are likely to occur now or in the near future.

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